The Association
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The Metallurgical Aspects Of Welding Low Carbon And Low-Alloy Steels.

By R. ERSKINE, B.Sc., A.R.T.C.

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CONTENTS.

INTRODUCTION AND SUMMARY.

Of recent years great developments have taken place in the use of welding in shipbuilding and other industries. Much research work has been done on the weldability of steels, but the practical application of the findings necessarily lags behind. The purpose of this paper is to present in simple terms the theoretical basis of metallurgical problems involved in welding ship and low-alloy steels and the practical methods employed in overcoming them. The paper also attempts to point out the significance of recent trends in welding, from a simple theoretical viewpoint. In shipbuilding, welding has certain obvious advantages over rivetting as a fabrication method, these being—speed of construction, hull tightness, weight saving and smoother hull contours. In addition it is easier to train qualified welders than rivetters.

The paper is divided into six main sections.

- I. Metallurgy of Constructional Steels.
- II. Classification of Electrodes.
- III. Weldability.
- IV. Preheating and Welding Practice.
- V. Design.
- VI. Conclusions.

The first section deals with the composition and properties of mild and low-alloy steels. The effects of various heat treatments on the metallurgical structure are discussed and illustrated briefly. Hydrogen weld-embrittlement theory is outlined.

A short description of electrode classification is included for completeness. This includes mention of electrode coatings, welding positions, electrical conditions and the reasons for using certain electrodes for specific purposes.

Weldability is defined and discussed in simple terms. It is pointed out that the term is diffuse and that many factors may influence it. Some of these are discussed at some length.

The first three sections set the problems in a somewhat theoretical way. The fourth section deals with the practical methods of overcoming these difficulties, namely by the use of preheating and of low-hydrogen electrodes, and by greater care in fit-up and welding. Reasons for doing so are discussed.

A section is included on welding design and its importance as a part of welding technology. The part which draughtsmen may play in welding is indicated.

Finally a broad view of the field is taken, pointing out the theoretical work being done, the limitations imposed by practice, and the necessity for co-operation. With the rise in the percentage

of welding employed in industry, there is a great need for all workers in the field, whatever their speciality, to increase their knowledge of the "other man's problems," so that a concerted effort towards welding of greater quality and efficiency may be made.

I. MATERIALS AND METALLURGY.

Materials.

Constructional steels consist of 95 per cent. or more iron, with from 0·1 - 0·8 per cent. carbon and varying amounts of the alloying elements manganese, nickel, chromium, molybdenum, vanadium, etc.; together with the impurity elements silicon, sulphur and phosphorus. The quantities of these elements vary from a mild steel with 0·1 per cent. carbon and 1 per cent. of alloying elements to a stainless steel which contains 0·1 per cent. carbon, 18 per cent. chromium and 8 per cent. nickel. Various constructional steel compositions are given in Table 1. Steel A is a typical mild steel, steel B a carbon-manganese alloy steel, C a low-alloy steel, and steel D is a random example of a modern high-strength weldable steel. The usual tensile properties of these steels are also quoted. Probably the most interesting property here is the yield point, since most structures are designed on the basis of this criterion. These yield points vary from 18 tons/in.^{2} in the mild steel to 32 tons/in.^{2} in the low-alloy steels.

Metallurgy.

It is important to the understanding of the metallurgy of welding to realise what happens to a steel when it is heated to a red heat and rapidly cooled. To explain this fully the equilibrium diagram of iron-carbon must be examined. A simplified version of the relevant part of this diagram is shown in Fig. 1.

A complete explanation of the diagram is outside the scope of this paper (see Ref. 1), but the most important features, as far as this subject is concerned, are as follows. When steels of the constructional type are heated to a certain temperature (from 730°C. to 910°C. depending on carbon content—see Fig. 1), the structure of the steel changes. Above the line DC the steel exists as austenite, which is an allotrope of iron, *i.e.*, another physical form. This material is single phased, that is—if it could be frozen as it was, it would appear under a microscope as equiaxed, polygonal grains. (Ref. 1, Fig. 170). These grains contain the carbon in "solid" solution.

Heat Treatment.

It is as well at this stage to define briefly the various common heat treatments used. These simple terms are often slackly used.

TABLE I.

Steel	Description	Chemical Composition									Mechanical Properties			
		C	Si	S	P	Mn	Ni	Cr	Mo	V	Yield Stress T./in.^{2}	Ultimate Stress T./in.^{2}	Elongation %	Brinell Hardness (approx.)
A	Mild	0·14	0·04	0·03	0·02	0·48	0·16	0·04	< 0·02	—	17·8	26·6	27	120
B	Carbon-Manganese ...	0·19	0·04	0·03	0·02	1·43	0·06	0·03	< 0·02	—	22·2	35·1	19	160
C	Low alloy	0·17	0·25	0·04	0·04	1·41	0·62	0·13	0·23	—	29·4	41·6	19	200
D	Weldable High-tensile	0·16	0·10	0·03	0·01	0·69	0·76	0·89	—	0·23	32·0	41·6	28	200

Most heat treatments depend on austenitising the steel first, and this consists of heating the material to a temperature 50°C. above the line DC (Fig. 1), the actual temperature depending on composition. As the temperature rises, the austenite grains coarsen, so the limit of 50°C. is usually observed so that the initial and hence the final grain size may be small, since properties depend to some extent on grain size. After soaking for some time to homogenise the austenite, the steel is cooled at various rates depending on the properties desired.

Annealing.—Furnace cooling. Soft and ductile.

Normalising.—Air cooling. Good all-round properties and rather less ductile.

Quenching.—Immersing in water or oil. Hard and brittle.

Tempering.—Reheating to restore ductility to a quenched material.

Most structural steels are put into service in the as-rolled condition, *i.e.*, air cooled from the temperature at which rolling finished. For steels which must have good and predictable properties, however, it is much more satisfactory to normalise after rolling. Quenching and tempering are used to develop high strength with a low-alloy steel.

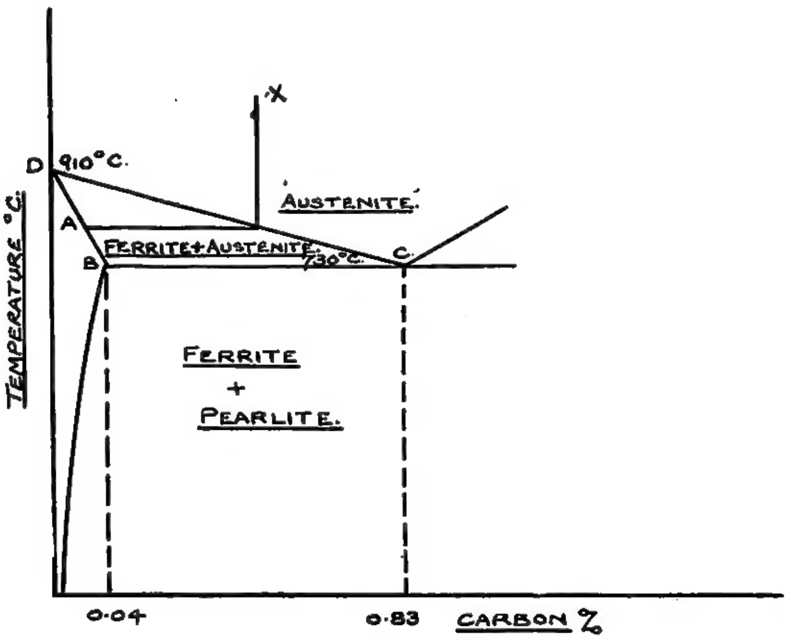

Fig. 1.—Iron-carbon equilibrium diagram.

The reactions on cooling depend on the rate at which the austenite is cooled from the high temperature. For simplicity and brevity, only three rates will be considered.

(*a*) Very slow or equilibrium cooling.

(*b*) Very fast or quench cooling.

(*c*) Some intermediate rate.

As the austenite is cooled it changes, or 'transforms' into other physical forms of iron. With a very slow cooling rate from the point X, the first material to crystallise out is a pure iron (ferrite) of composition A (Fig. 1). The remaining austenite becomes progressively richer in carbon while the low-carbon ferrite is precipitating, till eventually the final material (composition C) transforms as the eutectoid (*c.f.* eutectic—low-melting)—'pearlite.' When the steel is prepared, polished to a very fine finish, and etched with a dilute acid it appears under a microscope as grains of white ferrite, together with the darker pearlite (Fig. 2). This is a typical mild steel (*e.g.*, Steel A). Pearlite is a physical mixture of ferrite and cementite (a carbide of iron). It has a lamellated appearance (Fig. 3), the spacing and coarseness of the lamellae depending on the rate of cooling.

Fig. 2.—Typical Mild Steel. ×100.

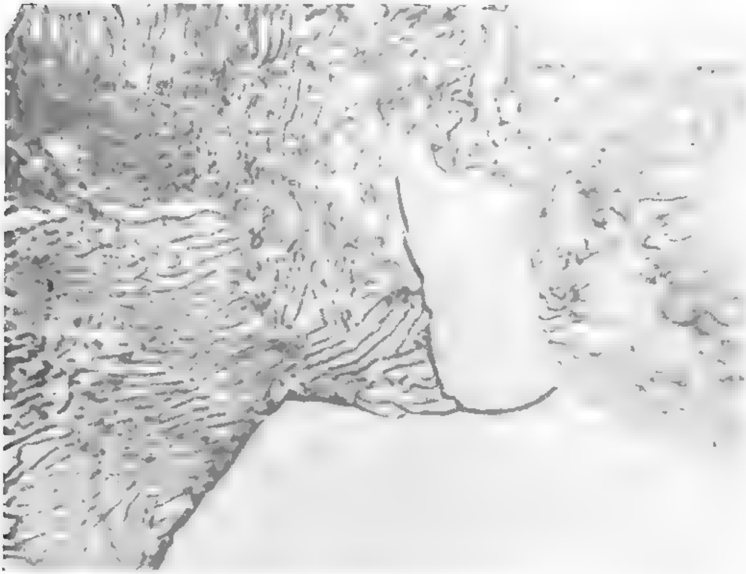

Fig. 3.—Pearlite. ×2000.

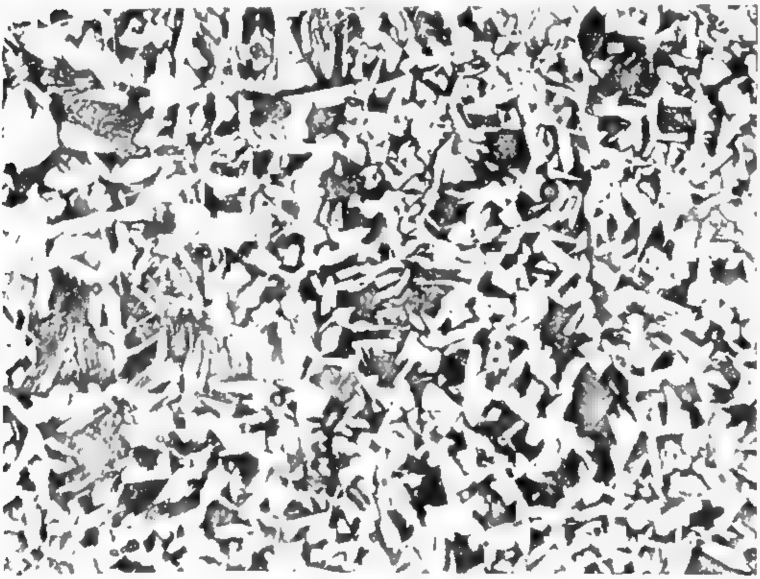

Fig. 4.—Steel B. ×100.

Steel B, with rather more carbon, would appear as in Fig. 4. Here there is naturally a greater percentage of the dark etching pearlite.

Fig. 5 is a photomicrograph of steel C in the normalised and tempered condition. Here it is seen that the carbon is more evenly dispersed than in the previous two steels and in this case, instead of being present as grains of the lamellated pearlite it exists as globules of carbide randomly dispersed.

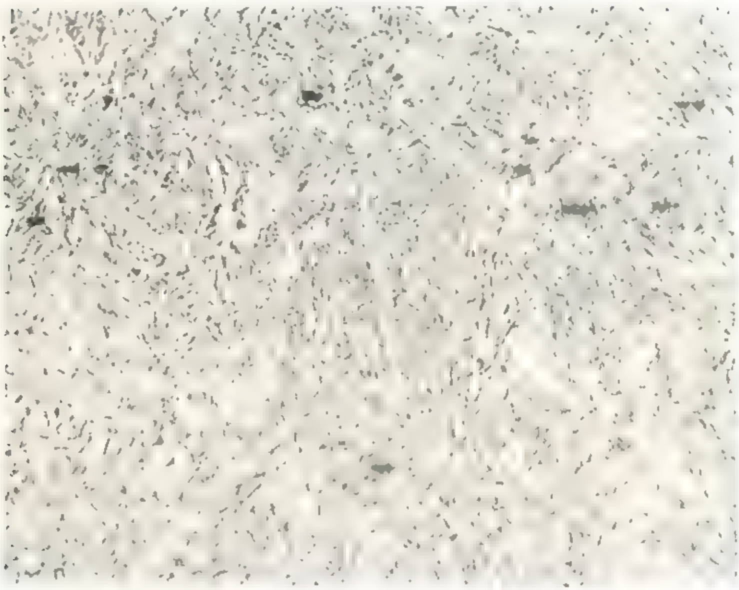

Fig. 5.—Steel C. ×100.

A fuller description of these features will be found in any elementary text-book on metallurgy (Ref. 2).

The preceding chapters have dealt very briefly with the structure and properties of commercial steels. These structures and those which will be discussed shortly are important to the understanding of welding metallurgy, particularly the thermal changes which take place in the zone immediately adjacent to the weld metal, known as the heat affected zone. The heat treatments described are thus important since almost the same changes take place in this small zone. We turn now to the other two cooling rates. The importance of these will be realised, for obviously the small adjacent zone, after being heated to a high temperature, is virtually quenched

due to the high extraction of heat by the surrounding cold metal. Now, when the austenite is cooled very fast, the 'equilibrium' conditions do not appertain and the austenite now changes, not into pearlite and ferrite, but into other harder substances. If the rate of cooling exceeds a certain value known as the 'critical cooling velocity' the steel will finally be in a very hard, brittle state and will consist of 'martensite,' shown in Fig. 6. The hardness of a martensite formed by a steel of composition C (Fig. 1) would be about 700 Brinell.

If the cooling rate is just below this critical value the austenite will transform into 'bainite,' which is rather softer and possesses some ductility. The hardness of this constituent would be about 500-600 Brinell. On slow cooling, such as an air or furnace cool the structure appears as Fig. 4, a normalised carbon-manganese steel.

Fig. 6.—Martensite. ×500.

It will be realised, of course, that these descriptions are very general. The subject of heat treatment and its metallurgical effects is immense. However, the basic problem in the welding metallurgy of these steels is the inhibition of martensite formation, and the replacement of this brittle material by one more ductile

and less likely to initiate small micro-cracks. It has been said that a certain cooling velocity must be exceeded before martensite can form. The extraction of heat from the affected zone of a weld is great, being rather higher than an air cool and slightly less than a quench, since the cold plate acts as a heat sink. With thicker plates the heat extraction rate can be very high indeed. Heat input is also a relevant factor, and minimum sizes of weld beads and electrodes are usually specified for this reason. The larger the electrode the greater the heat input and the less likely is cracking in the weldment.

It now remains in the metallurgical section to discuss the mechanism by which cracks form in the heat affected zone of a weld. The theory is rather extended so a simple survey will be given here.

Hydrogen Theory of Weld Embrittlement.

The coatings of metal-arc electrodes contain, to a greater or less extent, sources of the gas hydrogen. These sources may be in the form of waterglass as binder, or as cellulose (a carbohydrate), or as the water of crystallisation of inorganic salts such as silicates or oxides. During the arcing process these hydrogen-bearing compounds break down and yield the hydrogen (atomically) in the arc. In this form the gas goes into 'solution' in the molten weld metal which has an almost insatiable capacity for absorption. However, when the metal solidifies it eventually turns from austenite to ferrite, and at this point the gas becomes greatly in excess of that which can be held in solid-solution. Now the gas comes 'out of solution' and the atoms begin to diffuse through the lattice structure of the metal into regions which are lower in hydrogen, namely, the heat-affected zone of the parent plate.

This mechanism is rather difficult for the average technician to understand. As an analogy, consider the solution of solid salt in a beaker of boiling water. A great deal will dissolve, but when the solution cools down it is supersaturated and 'throws out' or precipitates its excess in the form of crystals of salt. This is roughly similar to the solution and precipitation of the gas hydrogen in weld metal.

When the gas in the atomic state enters the heat-affected area it immediately diffuses into voids and interstices in the imperfect metallic lattice. These gaps are formed by the tiny non-metallic inclusions and by other discontinuities in the crystal structure. The atoms now molecularise and in doing so increase the internal gas pressure by the square of the previous value, *i.e.*, that in the atomic state. Thus regions of great pressure are built up at various points, and when this force is added to the internal transformation strains, it is thought that micro-cracks are initiated from the

inclusion and imperfection notches. In the weld metal proper the hydrogen may congregate to such an extent that the pressure causes a fissure or small crack (Ref. 3). As far as cracking in the heat-affected zone is concerned the theory has been rigorously investigated since it was put forward by Hopkin in 1944, and appears to be quite valid. The fact that hydrogen is the main gas present has been shown experimentally by the British Welding Research Association (Ref. 4). Later in the paper the method of cutting down the 'hydrogen potential' will be discussed.

II. CLASSIFICATION OF ELECTRODES.

For a complete survey of this subject, the best source of information is undoubtedly the British Electrical and Allied Manufacturers' Association's *Guide to British Electrodes* (Ref. 5), or the appropriate British Standard (Ref. 6). The former is an excellent pamphlet, giving the various types of electrodes, their uses, the electrical conditions pertaining to them, and much interesting information.

The classification is based on three figures. The first gives the coating type, the second the welding positions possible, and the third the welding current conditions suitable to the electrode. Table II shows the six types of electrodes and their operating characteristics. It is outside the scope of this paper to digress on the classification, and a study of the pamphlets will be amply repaid.

TABLE II.

Class	Covering Characteristics	Particular Operating Characteristics
1xx	Cellulose type; light slag	Deep penetration
2xx	Rutile type; viscous slag	Flat and horizontal-vertical
3xx	Rutile type; fluid slag	Vertical and overhead
4xx	Iron oxide type; inflated slag	Deep groove welding
5xx	Iron oxide type; solid slag	"Touch" welding
6xx	Lime-Fluopar type; basic slag	Used for "difficult" steels

Hydrogen in the Coating.

Some mention must be made here of the constituents of the coatings with respect to their hydrogen contents. Hydrogen is present in the coatings in the form of water or as organic compounds. An example of the latter is the carbohydrate cellulose in class 1. The water can exist as waterglass used as binder, or in combination with the coating constituents such as sodium silicate and clay. Generally speaking, the hydrogen is present in two distinct forms – either in chemical combination whence it cannot be removed without very high temperature treatment, or in the 'mechanically' held form of water of crystallisation when baking at 100°C. - 400°C. removes it.

The first four classes possess approximately the same potential of diffusible hydrogen, and Classes 5 and 6 considerably less (Ref. 4). Class 5 is, however, very restricted in application. Class 6 electrodes, the low-hydrogen types, have a coating consisting mainly of calcium carbonate and fluospar and the hydrogen is present in a removable form. This ensures a very low potential of hydrogen for entry into the arc and so vastly reduces the possibility of hard-zone cracking. Naturally the coating may absorb some moisture from the atmosphere, so it is usual to store these electrodes in a dry, warm room and to bake them at 100°C., or in very special cases 400°C., for one hour before use. In this condition a commercial Class 6 electrode may contain as little as 0·30 per cent. moisture, and a particularly special brand 0·15 per cent. As a comparative figure a Class 2 electrode may contain 3·5 per cent. moisture.

Electrodes for Specific Purposes.

Certain electrodes are particularly applicable for welding in a particular position, or for a specific purpose There are various reasons for this. It may be that because of arc characteristics, slag type, or appearance of deposit a certain electrode might be particularly suited to a certain job. For example, if the slag volume is low the electrode will be applicable to all positions of welding, as in Class 1, as contrasted to the dense, voluminous coating of Class 4 deposits which limits this class mainly to welding in the flat position. Class 5 electrodes yield a deposit of good appearance and are easy to use. Thus they would be applied to such things as fillet welds where appearance was important and strength not so vital, since the degree of penetration is low and the weld metal soft.

Class 6 electrodes, the comparatively 'low-hydrogen' types have many excellent characteristics. The deposit metal has very good physical properties, including high notched-impact values and good ductility. In addition the weld metal has good resistance

to cracking, both hot (Ref. 4) and cold (Ref. 3), and the electrodes are less sensitive to plate composition than the other types. In this last respect these electrodes are largely used in welding high tensile steels, steels high in carbon and sulphur, and also steels of unknown composition, a factor which unfortunately arises too often in constructional work. These electrodes are slightly more difficult to use than the others, and a short arc must be maintained to keep down porosity. Training will soon overcome this, and must do so, since these electrodes are so superior in properties.

III. WELDABILITY.

The word 'weldability' has been in current technical use for some years now. Nevertheless it is very often used slackly and it is essential to realise that it is not just another property of the steel such as ductility, strength, and so on.

Perhaps the best single definition is as follows : 'Weldability is the capacity of a steel to be fabricated by a prescribed welding procedure without detriment to its service properties.' Many factors, some technical, some personal, go towards making up this complex property and these may be briefly listed.

(1) Suitability of material metallurgically.

(2) Quality of electrodes.

(3) Efficiency and skill of operators.

(4) Surrounding conditions.

Though weldability is such a broad term, it can be divided into two distinct fields. Firstly, the materials and their ability to undergo the thermal cycle of welding satisfactorily—this side will be referred to hereafter as 'material weldability.' Secondly, the engineering aspects, including processes, equipment and the human element. This sub-division is the very essence of welding technology—on the one hand metallurgy and the scientific approach, and on the other the fabrication and service problems. It is not possible to digress at great length on this vast subject, so a summary will be given, together with references to more extensive reading. The section is sub-divided into four divisions—weldable steels, electrodes and their approval, weldability testing, and lastly personnel and conditions.

Weldable Steels.

As higher strength steels are demanded for structural work, so the difficulties of welding these steels become more acute. As the alloy content of steel increases so the degree of quench to obtain maximum hardness becomes less severe. In other words, alloy

steels harden more easily under similar conditions of quenching. The transformation of austenite to martensite results in internal stresses, due to the opposing forces of an expansion on that change, and the natural contraction of shrinkage. The steel is then brittle and very prone to cracking. Add to these internal stresses external restraint together with hydrogen pressure and the heat affected zone becomes very susceptible to cracking. The development of steels with high strength yet a good reaction to welding heat is one of the most potent problems of welding technology. It is essential that the carbon content be kept below 0·20 per cent., which limits the strength. This can be raised by a judicious choice of alloying elements together with suitable heat treatment. Examples of steels such as this are given in Table 1 (C and D). Such steels are usually formulated after extensive experiments, for the mechanical properties must also be satisfactory.

In the question of material weldability it is important to realise the metallurgical reasoning involved. For higher strength steels, plain carbon materials are obviously unsuited to welding since with a carbon content of 0·5 to 0·7 per cent. the transformation stresses would be very high indeed and quench cracking would inevitably ensue. It is reckoned that 0·5 per cent. plain carbon steel is the highest content that can safely be welded without the use of preheat, even with low-hydrogen electrodes.

Alloy addition is the principal means of obtaining increased strength in a steel of given carbon content, when the quenching rate is less than required for the full hardening of plain carbon steels. So it is that low-alloy steels are used in preference. However, to keep these steels weldable is quite another matter since under bead or hard-zone cracking becomes more prevalent due to this easier hardening. The carbon content must then be kept down and the strength maintained by alloys which strengthen the ferrite (such as nickel), by precipitation-hardening alloys, or by quenched and tempered steels which can develop a high yield strength with a low carbon content and suitable alloy additions.

There are, of course, a multitude of other requirements for a weldable steel, but these can only be specified and obtained by the metallurgist on the job. The particular service requirements must be borne in mind when choosing a steel and a welding process. A simple example of this is that a welded fabrication requiring a high degree of notch toughness should be made of fully-killed (*i.e.*, totally deoxidised) steel with low grain-coarsening tendencies. A very coarse grain in the heat affected zone would produce a weak and notch-sensitive area, susceptible to cracking. Grain-coarsening may be limited in practice by decrease of heat input, or by multiple passes which causes a grain refining on one run by the 'normalising' process of the ensuing run.

Electrodes and Their Approval.

The weld metal plays an obviously vital part in any welded joint and so must be of good strength and a high degree of cleanliness. The electrode wire must be of good quality steel (low in sulphur to minimise hot cracking). Electrodes should be stored under proper conditions as indicated on the packets by the makers. With Class 6 electrodes much greater care is needed, and warm, dry conditions of storing are essential together with baking at the prescribed temperature for not less than one hour. After baking the electrodes must be used within four hours or they will absorb moisture from the air. The fulfilment of these conditions is necessary so that the potential hydrogen value should be as low as possible. A recent paper by Cottrell and Winterton (Ref. 4) has emphasised this point yet again.

Most large organisations which do a considerable amount of welding work have a series of tests through which a new electrode must pass before being approved for use. These tests will depend largely upon the proposed application of the electrode. For example, in the shipbuilding industry the tests involved would be longitudinal and transverse bend tests on a butt weld, an all weld-metal tensile specimen, weld-metal Izod or Charpy specimens, and perhaps a special weldability test such as the restrained butt-cracking test (see later). Over all these tests would be the important criterion of useability ; that is, the ability of an average welder to manipulate the electrode and to produce radiographically satisfactory welds in the welding positions specified. This question of electrode approval is very important, and not only should electrodes be approved for a particular job, but they should be checked at intervals for consistency.

Weldability Testing.

Weldability can only be assessed by testing the actual welds, either the production job by non destructive methods or a laboratory facsimile by various research means. This section will be further sub-divided into :—

(*a*) Research methods of assessing material weldability.

(*b*) Metallurgical examination of welds.

(*c*) Non-destructive testing of welds.

These three sub-sections bridge the gaps from research, through the production control metallurgist, to the examination of the production article.

(a) *Research Methods.*

There are many research tests used to investigate the material aspect of weldability, that is, the inherent ability of a material

to undergo satisfactorily the metallurgical changes involved in the welding process. The four main tests are described. Firstly the Reave Test (Ref. 7) which has been modified recently in method and especially in interpretation by the British Welding Research Association. The second test is the Controlled Thermal Severity (C.T.S.) Test of B.W.R.A. These two tests can be discussed together, being very similar. Reference will be made to the second test in the text.

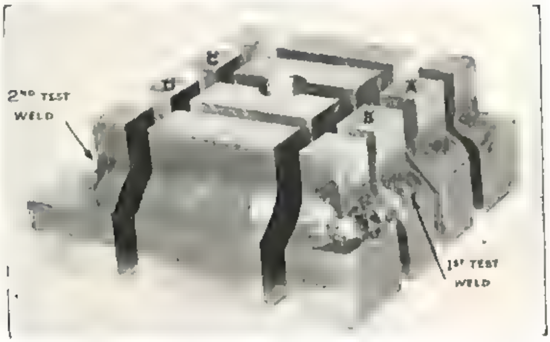

Fig. 7.—The C.T.S. Test.

The Crack Thermal Severity Test consists of laying down a fillet weld (Fig. 7) and measuring the amount of cracking on the vertical legs after sectioning and polishing. The block is sectioned as in Fig. 7 and the percentage cracking measured on the vertical legs of both sides of A and the remote side of B. It is possible to increase the rate of cooling by raising the gauge of the electrode, increasing the plate thickness, and increasing the thermal severity (Ref. 8). This test gives comparative results, and only when one steel gives cracking and another none under identical conditions can the second be said to be superior to the first. Nevertheless the test has proved very useful in the development of material weldability investigations. Cottrell (Ref. 9) has extended its use greatly and has co-related the cracking results with rates of cooling, end of the austenite-martensite transformation, and hydrogen potential, to a remarkable degree. These researches bear out fully the hydrogen embrittlement theory outlined earlier.

Another cold-cracking (hard-zone cracking) test is the Sims and Banta Test. This simple and effective test consists of a bead of weld metal laid down on a 3″ × 2″ strip of the metal, maintained

at 21°C. The strip is then sectioned longitudinally and the length of underbead cracking measured. The test has not been used extensively in this country (Ref. 10).

The Lehigh Restrained Butt Cracking Test (Ref. 11) is perhaps one of the most useful of all since it compares electrodes, steels and position of failure. The test consists of a weld run laid down on a grooved plate 12″ × 8″, under controlled speed and electrical conditions and with varying degrees of preheat and restraint (Fig. 8).

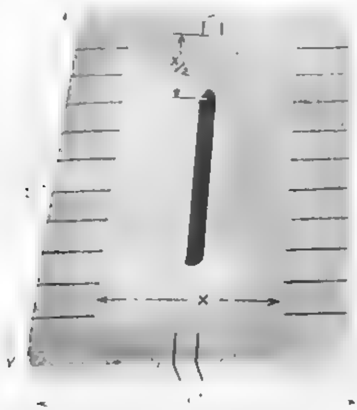

Fig. 8.—The Lehigh R.B.C. Test.

The restraint is measured by the distance X between the slots. Obviously if the plate material, the electrode and the conditions are maintained constant the restraint level at which cracking first occurs can be quoted. Comparisons can therefore be made of electrodes or steels, and also of the effect of preheating on restraint level. This test has many attractive features, since it closely simulates practical conditions, and has been shown by extensive investigations to be sound and very sensitive. After sectioning, the surface is ground smooth, etched and photographed. Fig. 9 shows a macro-photograph of a cracked weld, the crack having probably initiated at the root notch and propagated through the weld metal.

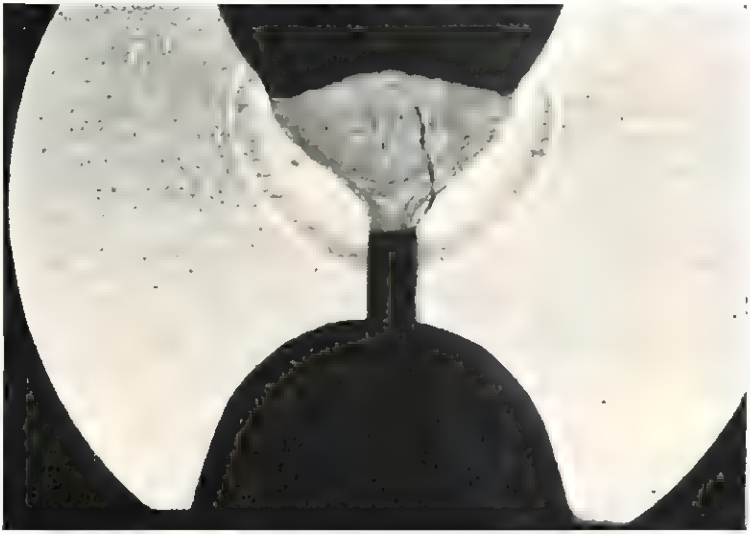

Fig. 9.—R.B.C. Macrospecimen. ×4.

Several other tests have been employed, but these four involve the basic principles of material weldability and its investigation.

(b) *Metallurgical Examination of Welds.*

Between the research methods described above and the non-destructive testing on the site lies the examination and testing of welds by metallurgical and mechanical methods. The mechanical methods have been previously described in the section on electrode approval and are fairly standard.

The next section will deal firstly with the examination of welds for soundness, and secondly with the adverse effects which certain common defects in steel have on welded joints. The soundness of welds is best firmly established by cutting out a transverse section, polishing it on successively finer emery papers, and etching it with a dilute acid. Such a specimen shows quite positively the degrees of fusion and penetration, and also any cracking which may be present. Fig. 10 shows a fairly sound butt weld with good appearance and fusion. The inter-penetration of the weld runs is inadequate, however, and the weld crowns are rather large, indicating over-welding.

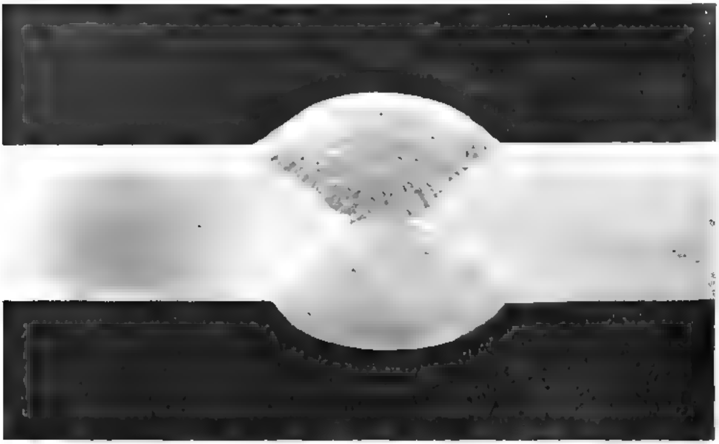

Fig. 10—Butt Weld. ×4.

This degree of preparation is good enough for many purposes and will enable the soundness of any weld to be assessed accurately. For research purposes it may be necessary to prepare a micro-specimen with a perfectly flat, scratch-free surface, etched in a one per cent, solution of nitric acid in alcohol. On examination under the microscope the detailed structure of the various components parent plate, heat-affected zone and weld metal, can be studied. Fig. 11 is of the junction of a V-prepared parent metal and the two adjacent runs of weld metal (distinguished by directionality). This photograph indicates quite clearly the excellent structure and cohesion of the welded joint on a very detailed scale. It is beyond the scope of this paper to enlarge on this side of welding metallurgy for the subject is a very specialised one. However, it may be said that the detailed microscopic study of weldments forms a large part of the research side and is essential to long-term progress.

In the course of the production of a steel plate, the molten steel is poured into an ingot where it is allowed to solidify. During the process of solidification certain segregations take place to the ingot centre. This results in the central zone being richer in carbon, sulphur and phosphorus. When the ingot is rolled out to a plate these segregations result in 'banding' which is known as 'segregation banding' to differentiate from other types of banding in steel. An example of this is shown in Fig. 12.

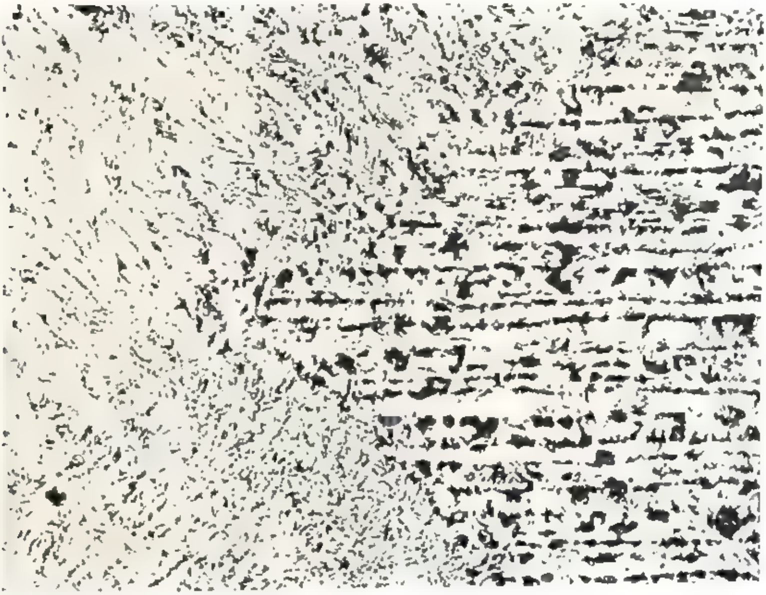

Fig. 11.—Weld Junction. ×100

Fig. 12.—Banded Steel.

The dark etching region is higher in carbon than the rest, and the danger in welding is that this band will penetrate into the heat affected zone (Fig. 13) and result in cracking due to greater hardening (Fig. 14).

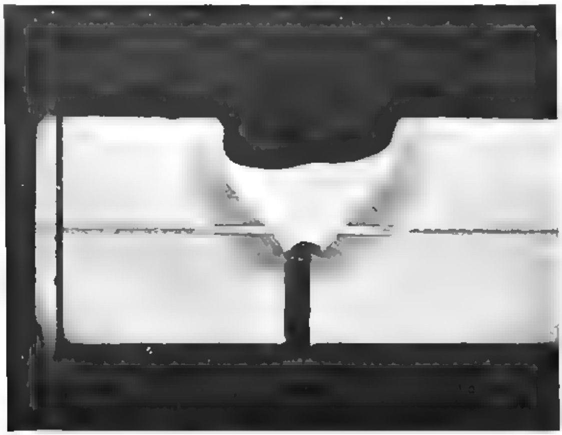

Fig. 13.—Band in Butt-Weld.

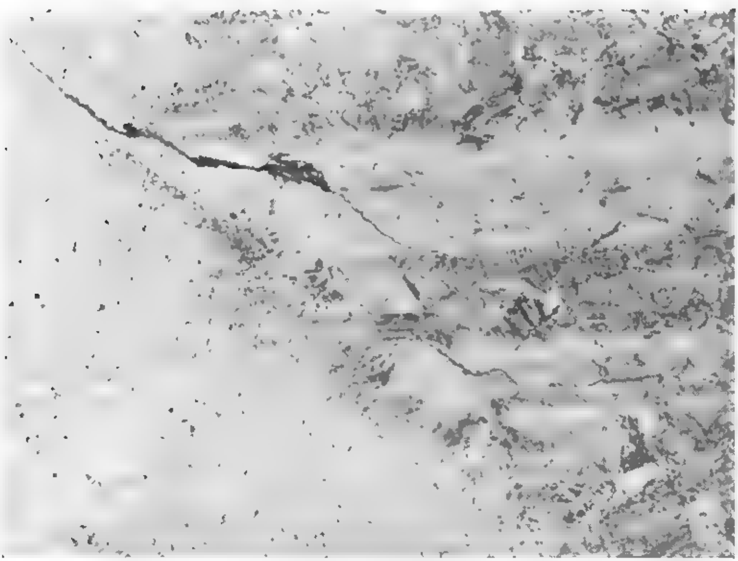

Fig. 14.—Crack in the junction area between band and heat affected zone. ×100.

Another type of segregation is that of non-metallic material. This may arise from the steel-making slag, from the runners furnace-to-ladle, or from the deoxidation processes. Whatever their sources these materials become elongated during rolling and result in a 'dirty' steel (Fig. 15).

Fig. 15.—Silicate Stringers. ×100 (reduced ×½).

Stringers tend to open up by the heat of welding, and so result in a weakened joint (Fig. 16). In addition it is obvious with a little thought that a steel such as in Fig. 15 will have low strength in the plate thickness direction and that fillet connections which may be stressed in that dimension are liable to premature failure.

The only solution to these problems is for steelmakers to produce cleaner and more homogeneous steels. In fact, it may be necessary to increase steel quality if the material is to be used in welded strength structures.

(c) *Non-destructive Testing.*

The task of examining welded joints not infrequently falls to draughtsmen, so it is appropriate here to digress a little on the subject of non-destructive testing. As its name implies this technique is one whereby the quality of a weld may be assessed on the site, where it is impossible to cut out a section. An important part of this work is simply the visual observation of the weld. If it is known that the welder is skilled and conscientious, then the appearance of a weld can tell a great deal about its quality. Such features as bead shape, surface concavity or convexity,

Fig. 16.—Effect of Stringers on a Fillet Weld.

degree of undercut and spatter can all be visually recorded from a fillet weld or butt weld.

The most common non-destructive testing method is radiography. Radiation is either by X-rays if a power source and suitable equipment is available, or by 8 (gamma) rays which can be obtained from a radio-active material such as iridium-192 or cobalt-60. The latter process is useful on an industrial site, where no power exists, though the quality of the radiographs are somewhat inferior. Such weld defects as slag inclusions, porosity, incomplete fusion, lack of penetration, undercutting and weld metal cracking can all be readily detected and consistently identified by radiography.

The ultrasonic method of flaw detection in welds is coming more into the field and offers a great deal of undeveloped potential. It is based on the back-reflection by flaws of short-wave vibrations. It requires, however, very skilled operators with wide experience of the apparatus. In addition, the type of flaw is very difficult to distinguish. The apparatus is highly portable and does not require access to both sides of a welded joint—an obvious advantage. This method is capable of detecting many types of flaws in welds, depending on their orientation and geometry, but for actual

identification, radiography has to be resorted to at the present state of knowledge.

A little reflection will reveal the obvious advantages of a flaw detection examination. A flaw may initiate failure in a welded structure, and if it is serious enough it must be removed and replaced by sound metal. Secondly, there is the psychological effect that welders, knowing that their work will be examined, tend to be more conscientious and painstaking. It is good policy to show the welder the radiographs of his own work, for in this way a mutual understanding will be built up.

Personnel and Conditions.

Lastly, it must be realised that two very important parts of weldability are the human element and conditions of work. It is a far cry from the carefully controlled laboratory test, where a machine regulates the electrical and mechanical conditions to a fine degree, to a shipyard or industrial site. Adverse working conditions will quite definitely lower weldability. Also the skill of the operator forms an integral part of this complex thing weldability. Along with the material aspects and the electrode side, the skill of the man on the job, together with his working conditions, must make up a large part of weldability in its broadest aspect. The obvious solution is to increase welding skill by training and to improve working conditions as much as possible.

IV. PREHEATING AND WELDING PRACTICE.

So far only a statement of the problems, and a short description of the materials and electrodes has been given. Now the methods employed in fabrication must be considered, and the simple theoretical explanation of these. Given a low-alloy or even more highly alloyed steel to weld there are several ways in which the adverse inherent weldability may be overcome. These methods fall into three main groups :—

1. Use of low-hydrogen electrodes.
2. Use of a preheating temperature.
3. By greater care in fit-up and technique.

The first two factors are bound up with the transformation of austenite to martensite and thus involve chemical composition of the plate, rate of cooling, and potential hydrogen. All effort in improving the material side of weldability is directed toward preventing martensite formation and subsequent hard zone cracking. The use of Class 6 electrodes greatly reduces the hydrogen factor in the latter. The use of preheating is directed toward the former, that is, the inhibition of martensite formation.

Preheating is the technique whereby the metal some six inches on either side of the weld preparation is heated to a certain temperature, say 100°C., so reducing the rate of cooling of the weldment. Since, as has been explained, the austenite must be cooled at greater than a certain critical rate before martensite forms, this reduced rate may bring about a transformation to the less brittle bainite, or at worst to a slightly more ductile martensite.

For a theoretical explanation of the effect of preheating the S-curve of isothermal austenite transformation must be consulted (for details see Ref. 1). This diagram deals with transformation at a fixed temperature, as distinct from the continuous cooling type which has been discussed previously. Firstly some explanation of the simplified diagram (Fig. 17) must be given.

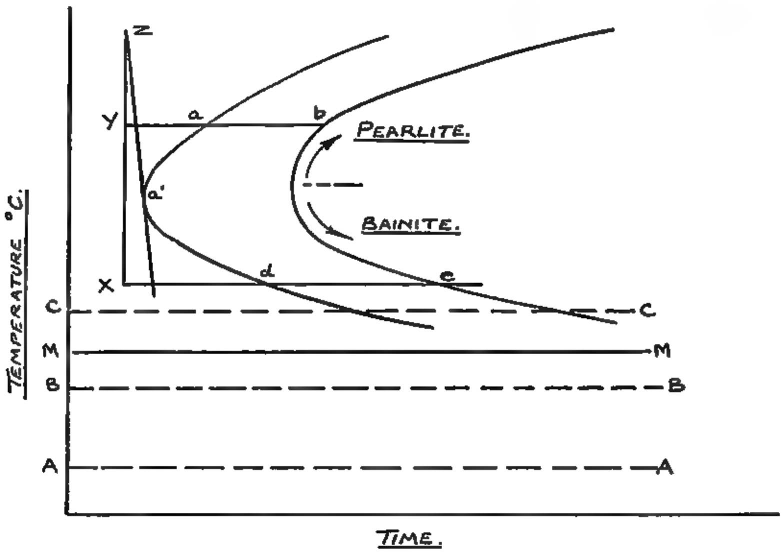

Fig. 17.—S-Curve for Isothermal Transformation.

If a steel is cooled from temperature Z to temperature Y, and held at this temperature, it will begin to transform from austenite at time 'a' and will end at time 'b', the end product being pearlite, ferrite precipitation being suppressed. Similarly by cooling rapidly from Z to X and retaining, transformation would begin at 'd' and end at 'e,' the product being a fairly hard bainite. If, however, the critical cooling velocity is exceeded, that is, the continuous cooling line has a slope steeper than 'Za^1,' the austenite will transform to martensite below the line MM. This temperature

varies for different steels, being generally lower the higher the alloy content, and about 300°C. for most low-alloy steels.

As we have seen, it is imperative to minimise the amount of martensite present in the heat affected zone, and this is done practically by preheating. If the preheat temperature is at BB, then only a small percentage of the austenite changes immediately to martensite. However, on cooling from the preheating temperature to room temperature AA, additional martensite forms from the untransformed austenite, but since the rate of cooling is slow, the thermal stresses are slight and cracking does not occur.

If the preheat temperature is at CC, that is, greater than the martensite temperature, then the austenite cannot transform to martensite so long as that temperature (CC) is maintained. This means that a more ductile product of transformation arises, namely, bainite, and the likelihood of cracking is decreased. Additional benefits of preheating are reduced thermal conductivity and concave weld beads due to weld pool superheating.

The third part of this section is a commonsense one with no theoretical basis. Obviously if a steel is difficult to weld satisfactorily, necessitating the use of low-hydrogen electrodes and preheat, then greater care must be taken in edge preparation and in fit-up so that root-gaps are even and that weld quality is as high as possible. This care is especially needful where class six electrodes are used, since these are at present susceptible to long-arc porosity and so cannot be manoeuvred (to overcome bad preparation) quite so easily as, say, a Class 2 electrode.

This section has dealt with the actual methods of overcoming inherent defects in the welding thermal cycle. The tendency for a quenched austenite to transform to a brittle martensite is overcome by preheating. The more heavily alloyed the steel the greater the preheat temperature, though there is obviously a practical limit. Incidentally, preheating is applied in practice by gas torches or electric strip heaters, and must be carefully thermally controlled. The tendency for hydrogen gas to encourage the martensite to crack is overcome by minimising the potential hydrogen available by use of Class 6 electrodes. Again, the more highly alloyed steel the greater the need for lower hydrogen values in the coatings. The two factors, preheating and Class 6 electrodes, are additive in their effects. That is, an extremely good low-hydrogen electrode might satisfactorily weld a material which could also be welded with an inferior electrode together with a small preheat. The better an electrode, the less preheat is necessary. Lastly, where expense and care are being lavished on the equipment for preheating, it is obvious that the edge preparation and fit-up, together with the skill of the operator, should be of the highest quality possible.

V. DESIGN.

The Role of Draughtsmen in Welding.

It happens not infrequently that draughtsmen become involved in some part of welding—be it design, overseeing, or inspection. Certainly it is essential that draughtsmen and designers be fully acquainted with the design problems in welded joints. This may be a question of referring to a given list of possible designs, if such exists, but in special cases the design of the joint and the preparation of the edges demands an intelligent observation of the conditions of welding and also of service. A good survey of the subject is given both in the *American Welding Handbook* (Ref. 12) and *Welding Practice* (Ref. 13) to which reference should be made. (Both these works are, incidentally, good books on this subject of welding technology).

That proper design is a most essential part of welding technology is obvious, since it minimises distortion and residual stresses, enables the welder to do a better job, and also economises on welding time and material. The particular purpose for which a weld is intended is, of course, the prevalent criterion. Thus if corrosion were the problem it would be essential to have no sharp irregularities where attack could concentrate. Again the particular type of stressing that will be involved in service must be considered—tension, shear, bending or torsion. Obviously a structure such as a ship, which is susceptible to brittle fracture must have as few notches as possible from undercutting, weld-cracking, or more especially from bad welding design.

Of the many aspects of welding technology that of design is one of the most important since it is the basis of the whole process and if done well can facilitate all future operations. However, the welding designer must have a wide knowledge of the theoretical aspects and essentially an understanding of welding shop practice since the recommendations which he makes on the production drawings will have to be carried out practically. Perhaps it would be as well to describe the range of duties which the weld designer, or more generally, the welding engineer, has to cover.

In any organisation which carries out a considerable amount of welding work it is essential to co-ordinate the various sections of welding—planning, design, manufacture, and inspection. This should be done by an engineer who functions both as a manager and a welding specialist. This man should have the final word in all cases of doubt, he should certainly check every drawing involving welding before it goes to production and should be consulted whenever difficulty is encountered. The value of a single voice of authority cannot be overstressed in this particular case. One of the most important sections of the work is, of course,

that of the preparation of welding drawings. Every detail must be made clear if the final job is to conform with the designers' intentions. The following information should be given on any welding drawing :—

(1) Material should be specified, preferably to a British Standard Specification. This is extremely important to ensure, or at least help to ensure, that incorrect metals or alloys are not used. The weldability of any particular material should be checked metallurgically in cases of doubt.

(2) Weld preparations should be clearly detailed, and the position, size, and type of fillet welds given. In the latter case whether the weld is continuous or intermittent should also be stated, as should leg length or throat size (or both).

(3) The welding process for each particular weld should be stated, and it is very desirable to use one process for a particular job, or at most two in particular cases.

(4) Welding sequence should be given, and also the amount and type of tack welds. The number of runs in any weld, also the type and gauge of electrode are details often omitted but essential for a balance between economic and sound welding.

(5) Lastly, any heat treatment required should be clearly detailed, and again metallurgical advice should be sought in cases of doubt.

It is obvious that one man could not have the range of specialist knowledge required for the details listed above and the co-ordinating welding engineer will call on various specialist sections. For example, on the metallurgical section for material and heat treatment information, on the drawing office for design and detail, on the welding shops for data on accessibility, availability of equipment, electrodes, and machining required. All these sections should concur in the draft drawing before the competent authority (the welding engineer) finally approves it. The welding engineer in any organisation has then ultimate responsibility for welding plant, design and drawings, workmanship (and the training of welders), materials, supervision of all processes, and finally inspection. Only by such close liaison and control can truly successful welded fabrications be made.

Let us look now at four aspects of this subject of welding design :

(1) Fillet Welds.
(2) Butt Welds.
(3) Flange Welds.
(4) General Design Considerations.

(1) Fillet Welds.

Although fillet welding is ostensibly a simple enough process the details should not be left to the welder, since there may be a tendency to overweld with consequent loss in productivity. The deposition of weld metal is expensive and in addition the distortion in any welded joint is roughly proportional to the amount of weld metal deposited. Therefore, weld metal should be held to a minimum, always keeping in mind the service required of the weld. Intermittent fillet welding is an attractive possibility since it achieves economy and cuts down distortion, though a balance must be sought between economy and required strength.

The minimum fillet size (expressed in leg length) to be used can be obtained from the relative thickness of the parts being joined and would vary from about $\frac{1}{16}''$ with a larger member of $\frac{3}{16}''$, to $\frac{1}{4}''$ with a 1″ plate. The particular electrode to be used for such sizes is also known for downhand welding and the relationship is roughly as follows :—

Fillet Size. (*Leg Length*).	*Electrode Size.*
$\frac{1}{16}''$	10 s.w.g.
$\frac{1}{8}''$	8 s.w.g.
$\frac{3}{16}''$	6 s.w.g.
$\frac{1}{4}''$	$\frac{1}{4}''$

Thus a particular gauge of electrode can be detailed for a particular weld.

While on the subject of fillet welds it is as well to mention that the use of bent plates and standard rolled sections should be exploited wherever possible and to do this the designer must have a knowledge of the range of available sections and must be on the lookout for their possible application. Since the strength of a fillet weld is proportional to the throat dimension of the cross section it is obvious that the parts must be assembled accurately, since a gap will reduce the effective throat thickness.

(2) Butt Welds.

The butt weld is easily the most important type of welded joint and correct preparation of the edges is essential to the quality of the final weld. In dealing with thin plates of $\frac{1}{4}''$ or less, it is often unnecessary to prepare the edges.

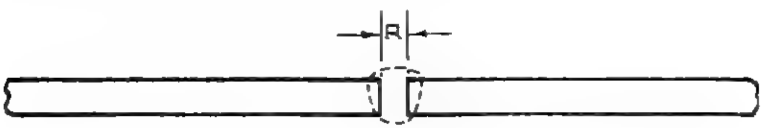

Fig. 18.

The root gap R may vary from 0″ for thin gauge material to $\frac{1}{16}$″ for $\frac{1}{4}$″ plates.

For thicker plates, however, a V preparation is required of which the most common are as follows for plates up to about $\frac{3}{4}$″ thick.

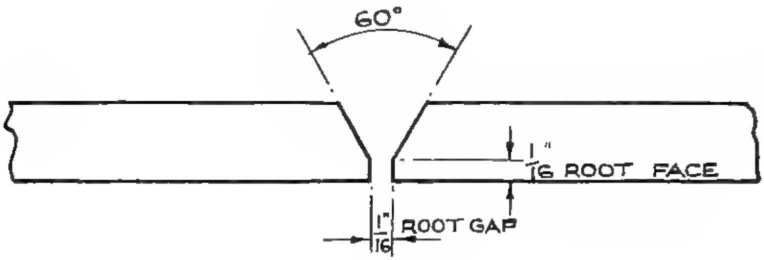

Fig. 19.

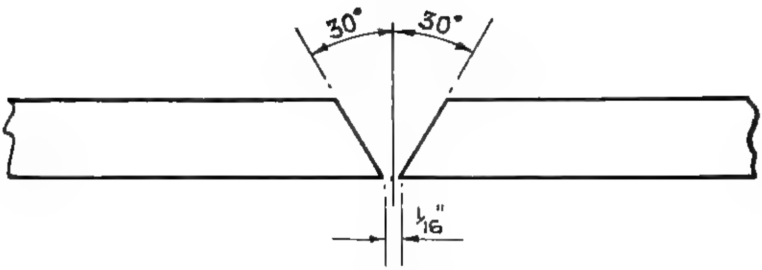

Fig. 20.

The minimum included angle is usually given as 60° for a downhand weld increasing to 80° for the more difficult overhead weld. However, electrodes are steadily improving in quality and it is less necessary to use different angles for the different welding positions. Obviously there must be a balance between the smallest angle possible and a sound, strong weld deposit. The root face calls for some discussion since although it is of great advantage to have a small root face to prevent burn-through by the intense heat of the welding arc, a varying root face is obviously dangerous, and is often obtained on commercial plates because of 'waviness.' The solution is generally to use a root face on short lengths, and a feather edge with a rather closer gap on longer plates. For special applications there are, of course, many forms of butt weld preparations some of which require machining. Butt weld preparations will naturally vary also with the material being welded and with the welding process being used, since the penetration achieved varies with the type of filler wire and the power input. It should be mentioned that the largest electrodes possible should be used compatible with the thickness of the parts being welded. Maximum deposit per unit time is achieved and distortion is reduced to a minimum. In addition a larger heat input cuts down the chance of underbead cracking.

The butt weld preparations just given are the most common for general constructional work ; however, there are many cases where a higher standard of weld is required, such as for a pressure vessel, or a pipeline, or where the weld has to withstand stress fluctuations. For these welds there are two main types of preparation, the first being where the 'second side' is accessible for welding when the preparation is as follows.

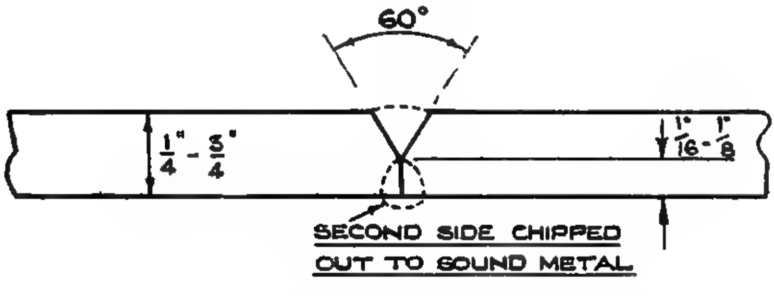

Fig. 21.

The second type is where it is not possible to weld the second side for various reasons (mainly that of lack of accessibility). The preparation here is as follows.

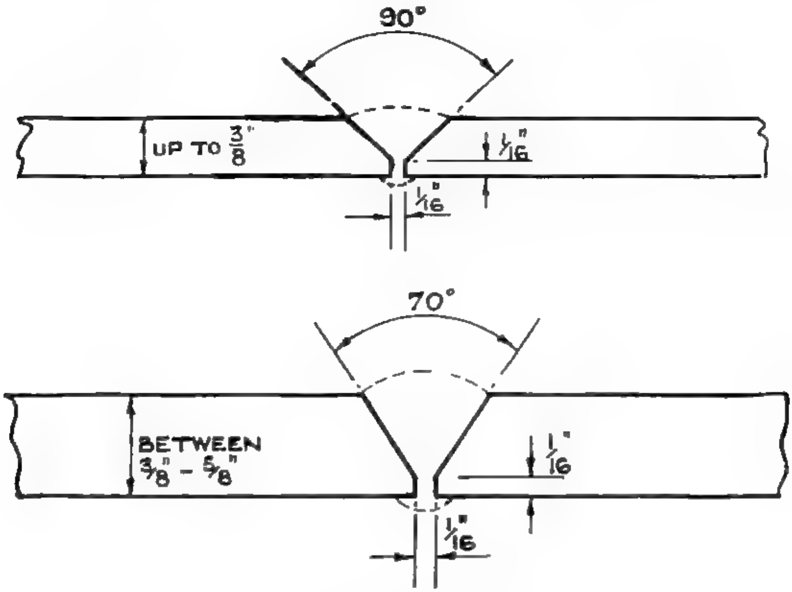

Fig. 22.

This preparation is designed to result in the weld bead just penetrating through, so that a smooth contour is obtained.

(3) **Flange Welds.**

A very considerable amount of flange welding is done in industry and the design of the joint is an important one since it applies not only to pipe welding but also to the many structures which have flanges. Generally speaking there are two types of pipe flange connections, the first being for the light duty when the preparation required is as follows.

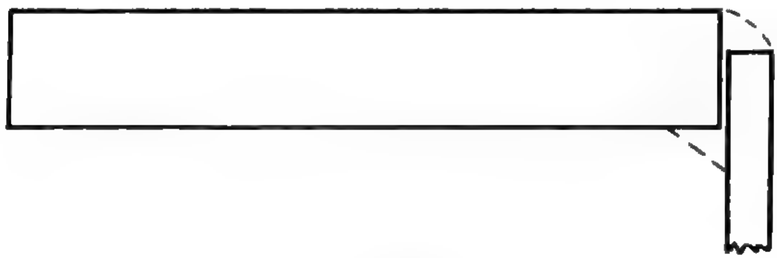

Fig. 23.

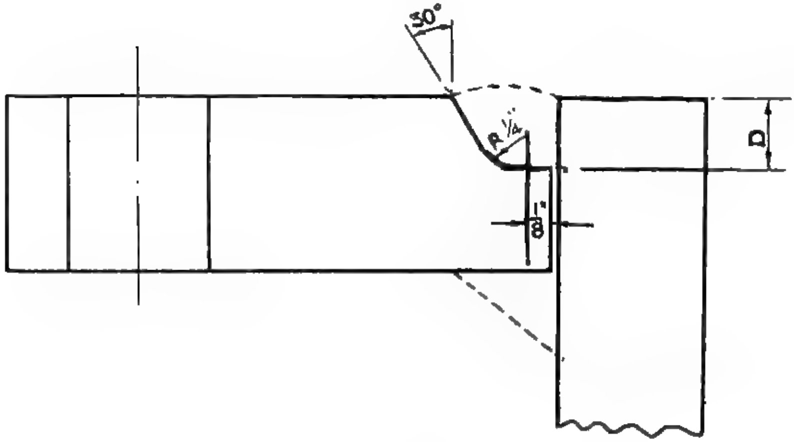

Fig. 24.

The second (Fig. 24) is for the heavier duty connections where a groove is necessary to ensure adequate weld metal penetration. The depth (D) depends upon the wall thickness of the pipe or vessel, and in certain cases where the wall thickness is great it is common to groove the underside as well, and to reinforce this with the usual fillet weld. Many factors must be considered in flange welding such as accurate positioning, accessibility for the welding electrode and prevention of excessive distortion, but if the design is carried out well the difficulties will be greatly reduced.

(4) General Design Considerations.

There are so many particular cases of welding design that it is quite impossible to discuss them all. Even very good books on weld design can be too specialised for all but a few readers. As has been said before, welding design must be carried out for each specific case, where all the facts regarding facilities and availability of material are known. However, there are certain basic lines which can be followed, although it is true to say that a 'good' welding design is also a matter of intuitive 'feeling of correctness' for the shape and contours of the job. This intuition can only come to a man of experience in welding technology.

Only designs applied to metal arc welding on mild and low alloy steels have been discussed and it must be understood that although the principles of butt weld design are generally applicable there will be variations for different metals and more particularly for the many different welding processes such as *Oxy-Acetylene Argon-Arc, Argonaut, Fusarc, Union-Melt* and so on. In cases

of doubt, the manufacturers of the equipment will provide the necessary information, or will indicate the source of such information It may be thought that this section has been overstressed, but it is true to say that if more attention were paid to the design of welded structures and the details of weld preparations, a great improvement in weld quality would follow. A balance must be sought between the theoretically correct and what is possible within the local practical limitations. It is most important to note that close liaison between all parties concerned is essential and in particular the welding shop should concur generally with the design. This means that a weld designer must have a good knowledge of welding shop practice, and must keep in close touch with his welders so that he may adapt his design to meet practical limitations or requirements, and achieve their confidence in him.

VI. CONCLUSIONS.

This is not the place to extol the virtues of welding as a fabrication process. These are manifold, and there is no doubt in the minds of those well acquainted with welding that it is the supreme method of joining metals and alloys. It has been the purpose of this paper, not so much to provide direct practical information about welding for a considerable amount of such information is readily available. Neither has it attempted to enlarge on the ever-increasing need for designers and draughtsmen to extend their knowledge of welding fabrication. This is, however, most essential, for the radical change from rivetting to welding brings with it a different line of thought, and a need for knowledge of design, processes and the theoretical metallurgical aspects which this paper has attempted to outline. It is very desirable that for a structure which is to be welded the designer should be able to choose a suitable steel, stipulate fit up conditions, welding technique, electrodes, and finally be able to carry out production inspection and some form of non-destructive testing. To do this he must necessarily possess personal knowledge, but a close contact with the metallurgist on the one hand and the welding foreman on the other is absolutely essential. Welding is the fabrication process with which it is most dangerous to meddle, and those using it must be experienced and should work as a team, designers and draughtsmen, metallurgists and welding engineers.

It remains now to draw a broad picture of the ferrous welding field. At the top level of research, more weldable steels are being experimented with, and rigorously tested. Several steels are already on the market which have a high yield (23-25 tons/in.^{2}) and are yet of high material weldability. On the material weldability side the cracking tendencies are being closely co-related to

composition, transformation characteristics, and hydrogen embrittlement. The solutions to the fundamental difficulties are preheat and the use of low hydrogen electrodes where necessary. These are now regarded as established facts. Electrode manufacturers are improving their products every day, producing better electrodes with improved useability wherever possible.

With these developments in materials and equipment the standard of skill must be raised so that the advantages gained are not easily lost, for no amount of research will improve the general quality of welds unless the skill and training of the welders remains high. Welding is without doubt the fabrication method of the future, and a great deal of application is necessary on the part of all concerned in it, be they designers, draughtsmen, manufacturers, operators, technicians or research workers, so that the general quality of welding may improve greatly.

ACKNOWLEDGMENTS.

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REFERENCES AND BIBLIOGRAPHY.

1. Henry, O. H., and Claussen, G. E. *Welding Metallurgy*, American Welding Society, 1949
2. Teichart, E. J. *Metallography and Heat Treatment of Steel*, McGraw Hill Book Co.
3. Rollason, E. C., and Roberts, R. R. "Journal of the Iron and Steel Institute," 1950, v. 166, p. 105
4. Winterton, K., and Cottrell, C. L. M. *Metallurgia*, January, 1954.
5. British Electrical and Allied Manufacturers *Guide to British Electrodes*.
6. British Standard 1719 : 1951. *Classification of Covered Electrodes*.
7. Reeve. "Transactions Inst. Welding," 1938, v.1, p. 13.
8. Cottrell, C. L. M. "Welding Journal," 1953, v. 32, p. 257s.
9. Cottrell, C. L. M. "British Welding Journal," April, 1954.
10. Hoyt, S. L., Sims, C. E., and Banta, H. M. "Welding Journal," Sept., 1945, p. 433.
11. "Welding Journal," Nov., 1947, p. 673s.
12. *Welding Handbook*, American Welding Society, 1950
13. *Welding Practice*, Vol. 2, in three volumes. Butterworth's Scientific Publications, 1952.

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24. ¾" Square Steel Tubes as Struts (30 ton yield).
25. ⅞" ,, ,, ,, (30 ton yield).
26. 1" ,, ,, ,, (30 ton yield).
27. ¾" ,, ,, ,, (40 ton yield).
28 ⅞" ,, ,, ,, (40 ton yield).
29. 1" ,, ,, ,, (40 ton yield).
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